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14. ABSTRACT

This project dealt with nanofabrication by metal-trilayer evaporation and liftoff. It included fabrication of Josephson-junction structures, and development of novel methods for metal liftoff at the sub-10-nm length scale. The ultra-narrow features developed in this project also have direct relevance to the nanofabrication of nanowire phase-slip qubits, which would provide an interesting alternative approach to superconducting qubits.

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Final Report For W911NF-04-1-0399 "Quantum Computing Graduate Research Fellow for Development of a Short Loop Superconducting Fab Process"

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This work extended the basic process development started in the master's thesis of Bryan Cord [1], and applied it to nanofabrication by metal-trilayer evaporation and liftoff. It included fabrication of Josephson-junction structures, and development of novel methods for metal liftoff at the sub-10-nm length scale. The ultranarrow features developed in this project also has direct relevance to the nanofabrication of nanowire phase-slip qubits, which are would provide an interesting alternative approach to superconducting qubits [2].

Suspended shadow-mask evaporation is a widely-used process for fabricating Al/AlO$_x$/Al Josephson junctions. Its minimal processing overhead and compatibility with high-resolution scanning electron-beam lithography (SEBL) make it ideal for rapidly generating simple superconducting circuits for quantum computing applications. The primary challenge in designing a shadow-mask evaporation process is the patterning of a suspended membrane, or shadow mask, in a two-layer photoresist structure. A junction is then created under the shadow mask via two aluminum angle-evaporation steps, with a brief oxidation to produce the tunnel barrier in between.

The resist bilayer in a shadow-mask process is typically composed of a thick support layer underlying a thin, high-resolution imaging layer. Previous shadow-mask processes have generally used poly(methyl)methacrylate (PMMA) as the imaging resist and PMMA/PMAA copolymer or low-molecular-weight PMMA as the support layer. The difference in the sensitivities of the support and imaging layers was usually enough to produce sufficient undercut for a clean evaporation and liftoff after a single exposure step. However, the fact that the imaging and support layers were developed simultaneously led to a degradation in resolution, as the additional development time required to create a sufficient undercut in the support layer caused an unwanted increase in linewidths in the imaging layer. In addition, the reliance on development to produce the necessary undercut made the process very sensitive to poorly-controlled factors in the development process; implementing this type of process in our lab showed very inconsistent results and spotty device yields.

By using poly(dimethylglutarimide) (PMGI) as the support layer and extensively characterizing its unique properties, many of these problems have been eliminated [2]. As the support layer in a suspended shadow-mask process, Poly(dimethylglutarimide) (PMGI) has several desirable properties. It is not affected by the organic solvents used to develop PMMA, while the bases that develop PMGI do not affect PMMA. As a result,

the two layers in a PMMA/PMGI bilayer can be developed independently; the resolution of the PMMA layer will not be affected by the development of the undercut layer. The decoupling of the two development processes means that the resolution of the process is limited only by the resolution of the imaging layer.

Since the primary factor limiting process resolution is now the PMMA imaging layer, considerable work has been done to push the resolution of PMMA past previously-established limits. Recently, developing PMMA below room temperature has been shown to increase the contrast of the resist, which in turn increases its final resolution[3][4][5]. The benefits of this effect appeared to increase as the development temperature was reduced, but no temperatures lower than -17˚C had been investigated in published work, leading us to hypothesize that it may be possible to reach even higher resolutions by further reducing the temperature, possibly close to the freezing point of the developer at approximately -80˚C[6]. Our experiments showed that this was not the case, however; below a certain temperature, the exposure process causes significant crosslinking of the exposed PMMA molecules, altering their dissolution behavior and degrading the contrast significantly (figure 1). Fortunately, we were able to identify an optimum development temperature; when PMMA is developed at this temperature, feature sizes of 10 nm and below are readily achievable even on a relatively low-cost 30 KeV electron-beam lithography tool (figure 2).

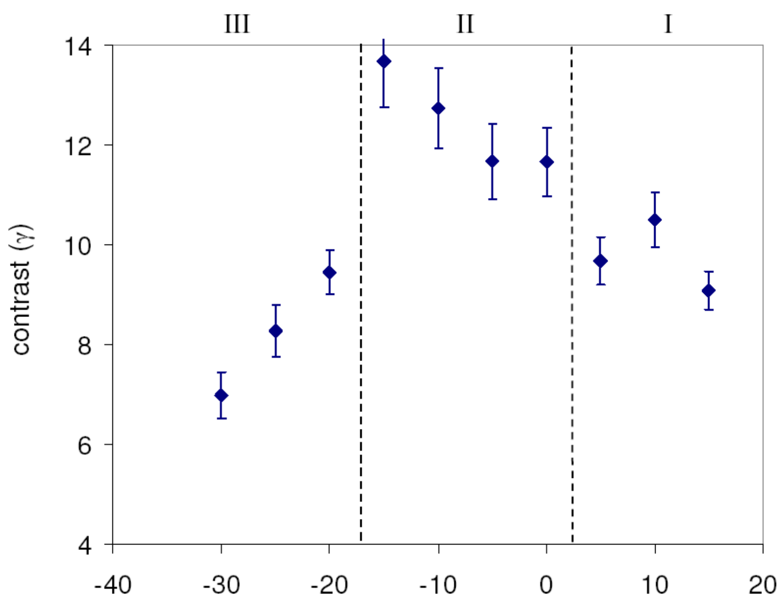

Figure 1: Resist contrast function γ as a function of temperature; to the first order, a higher γ value corresponds to higher lithographic resolution. Three temperature regimes are visible in the plot; in region I, contrast is degraded by development of partially-exposed resist at the edges of the exposure area. In region II these partially-exposed polymer chains are frozen in place, enhancing contrast, and in region III the presence of increasing amounts of crosslinked PMMA hinders the

development process of highly-dosed resist and sharply degrades the contrast. From this chart, the optimal range of development temperatures appears to fall between 0˚C and -15˚C, with optimum contrast occurring at -15˚C.

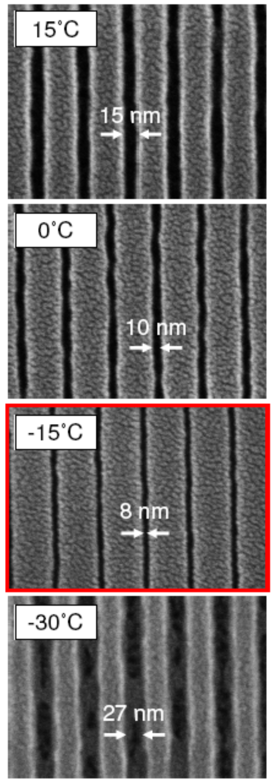

Figure 2: SEM images of 60-nm-pitch gratings developed at 15˚C, 0˚C, -15˚C, and -30˚C and etched into a Si substrate, showing the minimum achievable linewidth at each development temperature. As the contrast data in figure 2 predicts, the resolution improves as the temperature is reduced, peaks at -15˚C, then drops sharply at -30˚C. The poor line-edge definition and bridging in the -30˚C micrograph are characteristic of sloped resist sidewalls, a symptom of poor resist contrast.

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** published outcomes of this program.